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PERFORMANCE AND EMISSION ANALYSIS OF POROUS MEDIA COMBUSTION CHAMBER IN DIESEL ENGINES USING KIVA 3V

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ABSTRACT

Higher powers at reduced fuel consumption and reduced emissions have become the norm for engine design today. With depleting fuel resources increasing pollution and cost associated with it, new means to deliver the necessary power are always constantly being investigated. Porous Media inside the combustion chamber presents an attractive option for delivering higher power, lower fuel consumption and reduced emissions. In this paper the authors have presented the performance of an IC engine embedded with a PM. The engine is modeled using modified KIVA 3V code and the results of the simulation are presented. The performance between PM and a non PM engines has been compared and illustrated at different revolutions and compression ratio. The results amply demonstrate the suitability of the PM in enhancing the efficiency and reducing the emissions.

KEYWORDS: IC Engines, PM, KIVA 3V, Emissions

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Original Article

INTRODUCTION

The fuel economy and exhaust emission regulations, new technologies, development time and cost reduction require increasingly sophisticated solutions to improve the diesel engine performance and reduce exhaust emissions In order to achieve desired improvements in engine development combustion process is the key and has to be approached in a different manner. Some of the methods that have been over a period of time include modification to injection systems in the form of high pressure injection, split injection, water injection etc. Similarly recirculation of exhaust gas, retarding the injection timing and modification of combustion chamber itself have also been tried and tested to enhance the efficiency of the combustion process and to reduce particulate emission. These modifications generally revolve around factors like modification in the fuel injection system, modification of combustion chamber or modifying the fuel mix.

Many researchers have explored the possibilities of new methods of combustion to make it efficient and reduce the emission process. Porous media combustion also referred to as filtration combustion in a packed bed is one of the most widely researched topics. The concept of porous media combustion revolves around a new type of flame with a exothermic chemical reaction experienced during the flow of fluid in a porous media. The term porous media combustion attributes its origin to Russian scientist [1]. With its unique characteristics the porous media combustion supports stability of combustion in a wide range of fluid velocities and air-fuel ratios. This stability in turn results in increased efficiency and reduced low NOx (Oxides of Nitrogen) and CO (Carbon Monoxide) emissions.

The advantages of liquid fuel combustion in porous media in regard to its advantages in supporting mixture formation and improving the combustion process have been investigated in the literature [2-6]. Martynenko et al. [4] proposed a numerical for fuel droplet collision with a high porosity PM employing collision probability and analyzed one dimensional heat transfer in a porous media. Kayal and Chakravarty [3] proposed numerical analysis of combustion inside a PM chamber with liquid fuel droplets suspended in air. A model based on a combined self-sustained liquid fuel vaporization–combustion system was developed using counter-flow annular heat recirculating burner fueled with kerosene by Newburn and Agrawal [4]. They were able to show enhanced combustion performance and reduced emissions. Mujeebu et al. [5, 6] presented reviews about liquid fuel combustion in porous media. Durst and Weclas [7, 8] proposed the concept of the PM engine and performed a systematic experimental study on a test engine, which was a modified diesel engine by inserting a SiC PM into the cylinder head between the intake and exhaust valves. They injected the fuel in to combustion chamber and subsequent process of combustion reaction occurred inside the PM. They demonstrated very low emission level, high cycle efficiency, and low combustion noise. Macek and Pola´sˇsek [9] employed numerical modeling to simulate the working process of a PM engine fueled with methane and hydrogen, respectively. Zhao and Xie [10, 11] investigated the interaction between a pressure swirl fuel spray and a hot porous medium of a PM engine using a two-dimensional numerical model.Liu et al. [12,13] evaluated the thermodynamic performance and analyzed the heat regenerative cycle in a PM engine. Ferrenberg [14] proposed a new design of PM engine in the form of regenerative engine with a porous insert, functioning as a regenerator.

The primary objective of the proposed work is to model and simulate the combustion and emission process in direct injection diesel engine in the presence of a Porous Media (PM) inside the IC engine. Since the primary goal is to study the influence of PM detailed modeling of PM is not presented and the model proposed in [7] is used for modeling purpose. In this paper a modified KIVA 3 code is used along with Wiebe's combustion model for modeling the combustion. Similarly emission of NOx and Soot are also suitably modeled. The modeled features are incorporated in the form of a modified KIVA code and the results of the simulation are presented. The analysis is specifically carried out in regard to fuel consumption, brake power delivered and emissions. These analysis were carried out at different revolutions and compression Ratios (CR).

MATERIALS FOR POROUS MEDIA COMBUSTION

A porous material means a material with connected voids that flow can easily penetrate through its structure. Combustion inside PM differs from conventional combustion having a high temperature gradient, free flame and a thin reaction zone. In comparison with conventional combustion chamber, combustion inside PM provides a reasonably high efficiency and better transfer of heat from burned gases to unburned mixture. Combustion inside PM provides better homogenization and significant amount of radiative heat is available for preheating the incoming air-fuel mixture. The technique of premixed combustion has been studied and applied successfully for combustion process. PM combustion presents an economically viable and technically suitable option for enhancing the performance of combustion.

Aluminum oxide (Al2O3), silicon carbide (SiC), and zirconium dioxide (ZrO2) are suitable material for PM and are recognized as high temperature resistant materials. SiC exhibits thermal shock resistance, mechanical strength, and conductive heat transport. SiC also has high melting point (3260 K), against cyclic thermal stress and strength retention at the peak regenerator temperature (1673 K), and excellent oxidation resistance. Metallic materials on account of their inadequate thermal stability and high thermal inertia are not suitable as PM. Fe–Cr–Al-alloys and nickel-base alloys have

been found suitable for some applications but they have comparatively less heat resistant. Structures of ceramic foams with different base materials were observed to possess high porosity, good conduction heat transport, low thermal inertia, low radiation heat transport properties and relatively high pressure drop. The effective thermal conductivity of anisotropic porous composite medium could vary largely with the component fractions.

There have been various attempts in the past to support engine processes by application of porous media (or similar structures) to internal combustion engines. Historically, a very early engine concept with application of a perforated plate (considered as a porous element) had been proposed by Lake and described in a US patent in 1918 [15]. This concept uses a ring , see Figure 1**,** made of a high-temperature material having radially oriented apertures. This invention concerns heavy-oil fuels and uses a perforated plate or wires to be electrically heated for improving ignition conditions. Additionally, it was assumed that the annulus plate or wire absorb enough energy from the combustion process, so that it might be used for preheating the fuel (charge) and for supporting the ignition process in the next engine cycle. This application does not apply a clear porous structure, but the annulus plate or wire plays a similar role.

APPLICATION OF PM IN INTERNAL COMBUSTION ENGINES

The major target for further development of the current IC engines is to reduce their harmful emissions to environment. The most important difficulty with existing IC engines that currently exists is non-homogeneity of mixture formation within the combustion chamber which is the cause heterogeneous heat release and high temperature gradient in combustion chamber which is the main source of excess emissions such as NOx, unburned hydrocarbons (HC), carbon monoxide (CO), soot and suspended particles. At present, the IC engine exhaust gas emission could be reduced by catalyst, but these are costly, sensitive to fuel and with low efficiency. Another strategy has been initiated to avoid the temperature gradient in IC engines that is using homogeneous charge compression ignition (HCCI)[16].

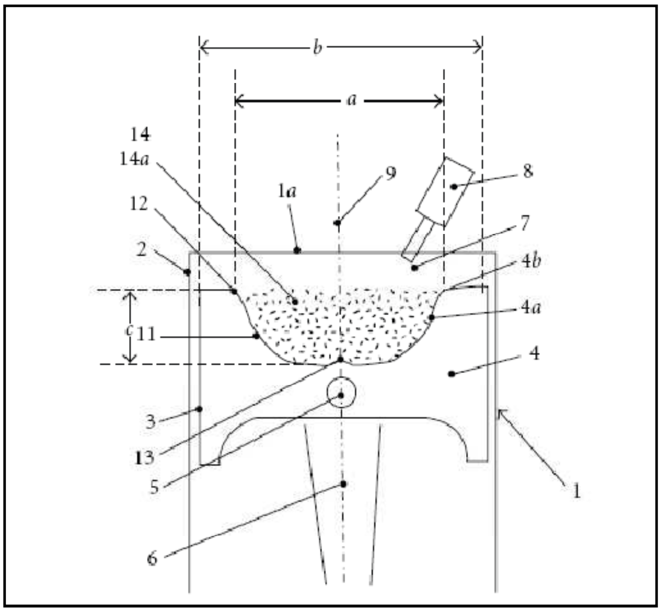

Figure 1: Typical Arrangement of a PM in an IC Engine [16](1-Cylinder; 2-Cylinder liner; 3-Piston Coat; 4-Piston; 4*a*-Piston bowl; 4*b*-Piston Surface;5-Gudgeon pin; 6-Connecting Road; 7-Combustion Chamber; 8- Injection Nozzle; 9-Longitudinal Axis; 11-Piston Bowl; 12-Corner; 13- Bowl hill; 14,14*a*-Porous Structure.)

COMBUSTION AND EMISSION MODELING

Wiebe function is used to predict the mass fraction burn and burn rate in internal combustion engines operating with different combustion systems and fuels [17]. Wiebe linked chain chemical reactions with the fuel reaction rate in internal combustion engines and his approach was based on the premise that a simple one-step rate equation will not be adequate to describe complex reacting systems such as those occurring in an internal combustion engine. Moreover, developing and solving rate equations which account for the simultaneous and sequential interdependent chain and chain branching reactions would be time consuming and tedious task. He argued that for engineering application the details of chemical kinetics of all the reactions could be bypassed and a general macroscopic reaction rate expression could be developed based on the concept of chain reactions.The Wiebe functions for the non-dimensional burn fraction x and its derivative w (burn rate) as functions of degrees crank angle can be written as

$$X=1-e^{-6.908(\emptyset/\emptyset\mathrm{d})^{m+1}} \quad (1)$$

$$W=\frac{dx}{d\emptyset}=\frac{6.908(m+1)}{\emptyset d}\left(\frac{\emptyset}{\emptyset d}\right)^{m} e^{-6.908(\emptyset/\emptyset\mathrm{d})^{m+1}} \quad (2)$$

or the non-dimensional burn fraction x and its derivative w (burn rate) as functions of time t can be written as

$$X=1-e^{-6.908(t/t\mathrm{d})^{m+1}} \quad (3)$$

$$W=\frac{dx}{dt}=\frac{6.908(m+1)}{td}\left(\frac{t}{td}\right)^{m} e^{-6.908(\mathrm{t}/td)^{m+1}} \quad (4)$$

The time it takes to reach maximum burn rate tm can be found by differentiating equation (4) and equating the result to zero

$$t_m=t_d\left(\frac{\mathrm{m}}{60908(\mathrm{m}+1)}\right)^{1/(\mathrm{m}+1)} \quad (5)$$

The corresponding burn fraction is

$$X_m=1-\exp\left(-6.908(t_m/t_d)^{m+1}\right) \quad (6)$$

From above equations (3) and (4)

$$X_m=1-\exp\left(-m/(m+1)\right)$$

Wiebe suggested the physical meaning of the exponent m which was based on equation (5), which shows that for a given combustion duration the time it takes for maximum burn rate to be reached is determined solely by the magnitude of m, which, in turn, determines the magnitude of the maximum burn rate (equation (5)).When calculating the heat release, prior knowledge of actual overall equivalence ratio is necessary. The term equivalence ratio is defined as the ratio of actual air-fuel ratio to the stoichiometric air-fuel ratio. This helps in fixing the mass of fuel to be admitted.In a combustion process, fuel and oxidizer react to produce products of different composition. The theory of combustion is a complex process and has been a topic of intensive research for many years. Let us represent the chemical formula of a fuel as $C\alpha H\beta O\gamma N\delta$.

Nitric Oxide Formation Model

The current approach to modeling NOx emissions from diesel engines is to use the extended Zeldovich thermal NO mechanism and neglects other sources of NOx formation [18]. The extended Zeldovich mechanism consists of the

following mechanisms

$O + N2 \longleftrightarrow NO + N$

$N + O2 \longleftrightarrow NO + O$

$N + OH \longleftrightarrow NO + H$

The change of NO concentration is expressed as follows:

$$\frac{d(NO)}{dt} = 2(1-\alpha^2)\frac{R1}{1+\alpha R1/(R2+R3)} \tag{7}$$

Where Ri is the one-way equilibrium rate for reaction i, defined as

$R1 = k_{1f}(N)_e(NO)_e$, $R2 = k_{2f}(N)_e(O2)_e$,

$R3 = k_{3f}(N)_e(OH)_e$, $\alpha = (NO)/(NO)_e$

Net Soot Formation Model

The exhaust of CI engines contains solid carbon soot particles that are generated in the fuel rich regions inside the cylinder during combustion. Soot particles are clusters of solid carbon spheres with HC and traces of other components absorbed on the surface. They are generated in the combustion chamber in the fuel rich zones where there is not enough oxygen to convert all carbon to CO2. Subsequently as turbulence motion continue to mix the components most of these carbon particles find sufficient oxygen to react and form CO2.Thus soot particles are formed and consumed simultaneously in the combustion chamber. The net soot formation rate was calculated by using semi-empirical model proposed by Hiroyasu et. al. (1983). According to this model the soot formation rate (index sf) and soot oxidation rate (index so) was given by

$$\frac{dm_{sf}}{dt} = A_{sf} dm_f^{0.8} p^{0.5} \exp\left(-\frac{E_{sf}}{R_{mol}T}\right) \tag{8}$$

$$\frac{dm_{so}}{dt} = A_{so} m_{sn}\left(\frac{p_{O_2}}{p}\right) p^n \exp\left(-\frac{E_{so}}{R_{mol}T}\right) \tag{9}$$

Where pressure are expressed in bar, dm_{sf} is the unburned fuel mass in kg to be burned in time step dt. Therefore the net soot formation rate is expressed as

$$\frac{dm_{sn}}{dt} = \frac{dm_{sf}}{dt} - \frac{dm_{so}}{dt} \tag{10}$$

IMPLEMENTATION OF PM INSIDE AN IC ENGINE USING KIVA-3V

`In this paper, a modified version of KIVA-3V [21] code was employed to simulate the working process of the PM engine. The computation mesh of the PM engine cylinder, where the disk PM regenerator is located is situated at the top of the cylinder and just beneath the cylinder head. The regenerator has a thickness of 10 mm, and a diameter of 9.4cm. The computational mesh used consists of 12000 cells at start of computation. The boundary condition applied to the momentum and energy equation with the assumption of zero gradients for temperature of both phase of PM and for species transport through the downstream boundary. Fuel is Diesel and, solid alumina spheres with a porosity of 0.4 is considered as the PM.

The computational period covers the interval from the intake valve close (IVC) to the exhaust valve open (EVO).For boundary conditions, constant temperatures were specified for the main cylinder boundaries; the side boundary of the PM was assumed as adiabatic, while at the top and bottom surfaces of the PM, there was heat exchange with the bulk gas phase. In this paper, a cold start of the PM engine was not considered, and the engine cycle was calculated starting at the IVC in a certain compress stroke after several cycles. Thus, the initial temperature of the PM regenerator was set at a constant value (of 433 K), which should be approximately equal to the average temperature of the PM during a continuous operation. The initial temperature for the bulk gas phase in the cylinder volume was specified as 400 K. Due to the high thermal capacity and a sufficient heat transfer coefficient between the PM and the gas, the temperature of the gas phase approaches the temperature of the PM very soon.

RESULTS

A modified KIVA 3V code is used to simulate and analyze the performance of the proposed model. The specifications of the engine modeled are illustrated in the Table 1. The necessary modeling parameters are fed and modeled initially using K3PREP solved using the code and processed using K3POST.

Table 1: Engine Specifications

Bore	13.716 cm^2
Stroke	16.51 cm
Length of Connecting Rod	26.3 cm
Squish	0.4221 cm
Compression Ratio (CR)	15:1
RPM	1600
Type of Fuel	$C_{14}H_{30}$

Similarly other factors that are considered in this model are listed in the Table 2. These parameters are vital for further analysis and modeling of combustion and emission.

Table 2: Factors Considered in Modeling of Combustion and Emission Process

Cylinder Wall Temperature	433.3K
Head Temperature	523.3K
Piston-Gas Side Surface Temperature	553.0K
Fuel Temperature at Injection	341.0K
Intake Surge Tank Pressure	1.96 e+6 dyn/cm^2
Intake Surge Tank Temperature	325.0K

The performance comparison between the engine with PM built in and without PM as per the engine operating conditions and specification listed in Table 1 and Table 2 is illustrated in Table 3

Table 3: Performance Comparison of IC Engine with PM and Without PM

	Without PM	With PM
Brake Mean Effective Pressure(bar)	9.589	10.284
Net Indicated Mean Effective Pressure(bar)	10.387	10.284
Gross Indicated Mean Effective Pressure(bar)	10.701	11.084
Brake Power(kW)	31.191	33.45
Net Indicated Power (KW)	33.793	36.05
BSFC (g/(kW-hr))	249.45	232.60
Fuel Flow Rate(lb/hr)	17.156	16.32

It can be observed from Table 3 there is clear increase in the performance of the engine embedded with PM. It can be observed when the performance is compared between engine having PM inside its combustion chamber and engine without PM, brake effective mean pressure increases by close to 6.5%. Similarly the brake power of the engine with PM is enhanced by nearly 7.24 %. In spite of the increased power the fuel consumption in the engine embedded with PM falls by 4.87 %. The facts points to the suitability of PM inside the combustion chamber to deliver higher power at lower fuel consumption. A 5 % reduction fuel goes a long way in terms of economy and also in terms of carbon foot print.

In order to elaborate on this aspect further, the simulations were carried out at different engine speeds than the maximum rated speed. The performance is compared in terms of the fuel flow rate and Brake power delivered at that particular speed. The simulation has been carried out a 3 different speeds of 1000 rpm, 1200 rpm, and 1400 rpm.

The Table 4 illustrates the performance of both the engines under varying revolutions in regard to the fuel flow rate. It can be clearly observed from the Table 4 there is marked reduction in fuel consumption in the case of engine embedded with PM.

Table 4: Performance Comparison of IC Engine with PM and without PM in Regard to Fuel Flow Rate

Speed (RPM)	Fuel flow Rate (lb/hr)	
	Without PM	***With PM***
1000	11.68	10.72
1200	13.92	12.87
1400	16.17	15.31

Similarly Table 5 illustrates the performance of the engine in terms of brake power delivered at varying revolutions. It can be clearly observed from the Table 5 that the power delivered by the engine with PM is higher at all the speeds simulated when compared to the power delivered by the engine without PM.

Table 5: Performance Comparison of IC Engine with PM and Without PM in regard to Brake Power

Speed (RPM)	Brake Power KW	
	Without PM	***With PM***
1000	21.23	22.04
1200	23.12	24.96
1400	27.48	28.84

Apart from the engine performance one primary factor that necessitates the use of PM inside the IC engine is its ability to reduce emissions. This section illustrates the effect of Compression Ratio (CR) in influencing the emission characteristics of the system. In this case also a comparison is worked out between engine with PM and engine without PM. The aim of the reduced compression ratio is to reduce the in-cylinder temperatures, hence flame temperatures during the combustion to suppress NOx emissions. Figure 2 and Figure 3 illustrates the formation of formation NOx gasses at different compression ratios of 18 and 17 respectively

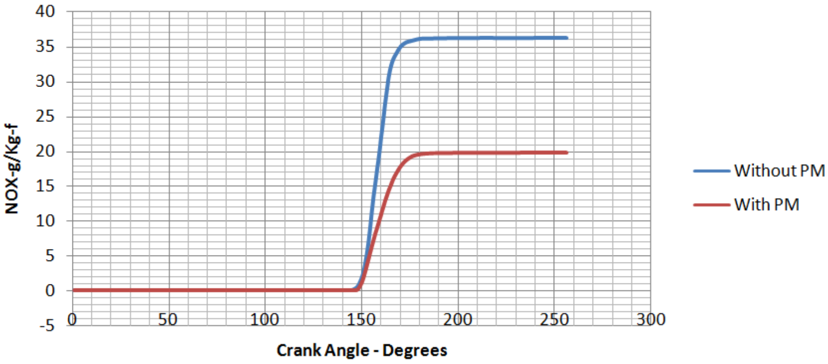

Figure 2: Quantification of Nox Formation at Cr 18:1

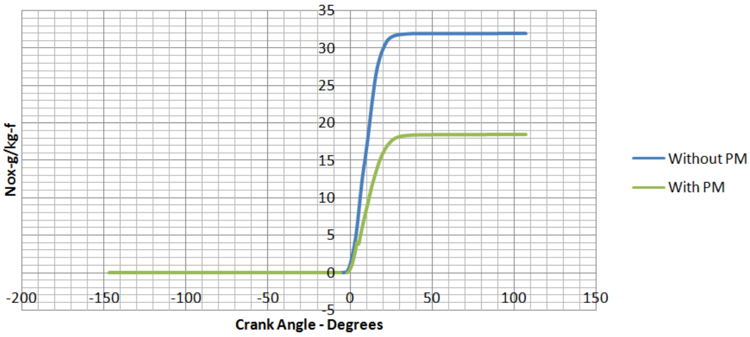

Figure 3: Quantification of NOx Formation at CR 17:1

It can be observed from the figures 2 and figure 3, the Compression Ratio (CR) has significant effect on NOx emissions. Lower CR results in reduced emission. Intrestingly when the comparison is done between the presence of PM and absence of PM there is significant reduction in the NOx emissions of engine embedded with PM than the one without PM.

`It can be inferred from the figure 3 when the CR is fixed at 18, the maximum NOx emission by engine without PM is 36.123g/kg-f, where as the maximum NOx emission by the engine embedded with PM is 19.7642 which totals to a reduction of 45.34 %. Similarly when the emission comparison is between the engines at CR of 17 (figure 4) the maximum NOx emission by engine without PM is 31.928g/kg-f, where as the maximum NOx emission by the engine embedded with PM is 18.464 which totals to a reduction of 42.17 %

The important pointer here is when the comparison is done between these two engines at different CR which have PM in their combustion chamber it can be observed that reduction in NOx emission between CR of 17 and a CR of 18 is 6.5 %. Whereas when similar compression is done for engines without PM the fall in emission is 11.5 %

Two aspects are amply clear from above discussions, the introduction of PM greatly reduces the NOx emissions and the next fact is with introduction of PM reducing the emission is possible even at higher CR.

Figure 4 and Figure 5 illustrates soot formation as function of crank angle and the comparison is made between engines with PM and without PM

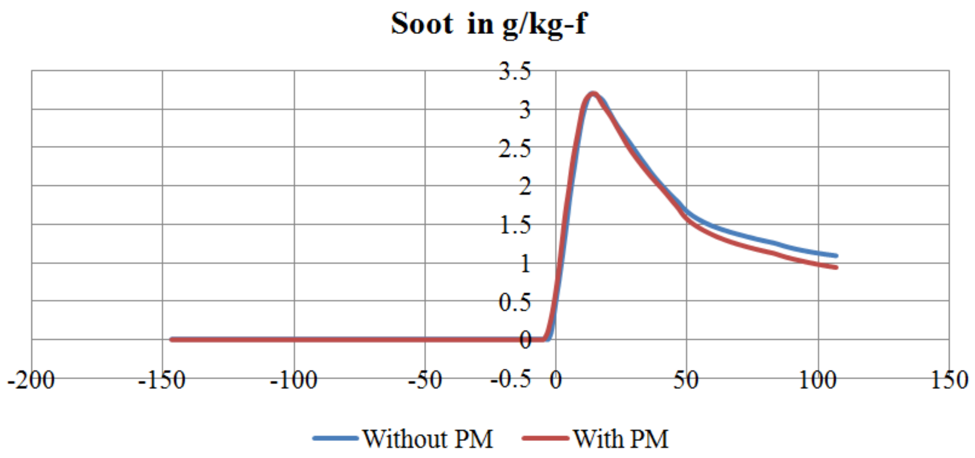

Figure 4: Quantification of Soot Formation at CR 18:1

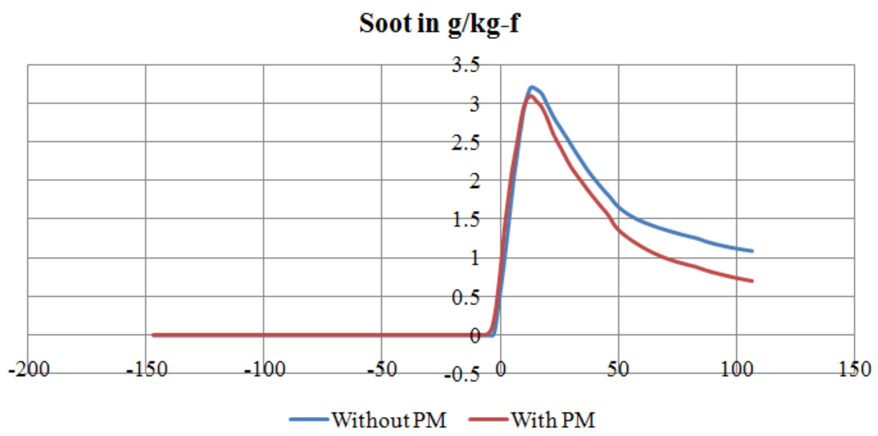

Figure 5: Quantification of Soot Formation at CR 17:1

It can be observed from the figure 4 and figure 5 there is reduction in soot formation with introduction of PM. It can also be inferred that the reduction is more predominant at lower CR than at higher CR.

CONCLUSIONS

The authors have studied and simulated the performance of PM inside a combustion chamber. The PM and the IC engines as whole was modeled using modified KIVA-3V code. The performances of the engines were studied to illustrate their capability in terms of brake power, fuel consumption rate, emission etc. It can be clearly observed from the results the introduction of PM inside results in increased power deliver at reduced fuel consumption. This phenomenon was uniform across different revolutions. Another important aspect that was clearly illustrated in this work is reduction emission with the introduction of PM. The introduction of PM reduced the NOx emissions to a great extent. The comparison for emissions was carried out in respect to compression ratio and it was observed that with introduction of PM it is possible to achieve lower emissions at even higher CR.

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